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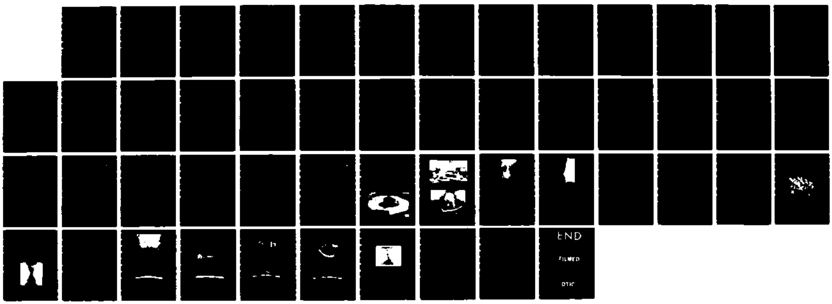

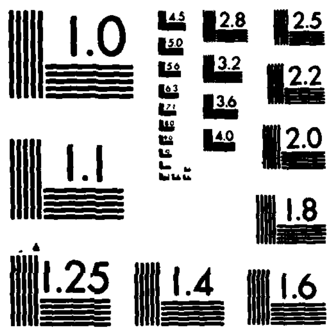

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MELBOURNE, VICTORIA

REPORT

MRL-R-958

EXPLOSION BULGE TESTING OF AUSTRALIAN *HY-80* STEEL PLATE

J.C. Ritter and B.F. Dixon

Approved for Public Release

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This report describes the program of explosion bulge testing of 50 mm thick Australian sourced HY-80 steel plate, supplied by Bunge Industrial Steels P/L to Industry Development Branch (NSW Region) to specification MIL-S-16216H (SHIPS). The testing was undertaken as part of the qualification of this steel in compliance with U.S. NAVSEA requirements. The report deals with the first series of tests which were unsuccessful, the testing of unwelded plate, the development of manual metal arc welding procedures and the investigation of candidate welding consumables which ultimately led to a successful test series.

The successful welds used low hydrogen electrodes of the AWS 10018 M type supplied by Philips (UK). The procedure followed a stringer-bead technique with strict limits on heat input, and a weld design incorporating a novel "top-hat" profile aimed at locating the weld toes (potential crack initiation sites, well away from the remaining weld fusion boundary (potential path for through-thickness crack propagation).

POSTAL ADDRESS: Director, Materials Research Laboratories
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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AUTHOR(S)

J.C. Ritter and B.F. Dixon

CORPORATE AUTHOR

Materials Research Laboratories
P.O. Box 50,
Ascot Vale, Victoria 3032

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CONTENTS

EXPLOSION BULGE TESTING
OF AUSTRALIAN HY-80 STEEL PLATE

1. INTRODUCTION

The impending construction of type FFG-7 frigates and the prospect of constructing new submarines in Australia have provided a strong incentive to establish an Australian capability for the manufacture of the high-strength quenched-and-tempered steels for naval construction. While the cost advantage is not necessarily large, the strategic advantage and the opportunity of obtaining steels of above-average quality are very desirable.

Of particular concern is HY-80 grade steel, a 3% Ni Cr Mo type which is specified for the more critical areas of the FFG-7 hull, and in the pressure hulls of a number of existing submarine designs.

In order to qualify this steel for the construction of overseas-designed vessels, it is necessary to meet appropriate quality and performance requirements, in particular mechanical properties which include the very severe explosion bulge test.

In this report the experimental work which ultimately led to a successful explosion bulge testing program is described.

2. DESCRIPTION OF THE TEST

The explosion bulge test was developed during 1949-1950 as a means of evaluating and assuring adequate performance of candidate steel plate and welding consumables in the construction of naval vessels [1,2]. The present test involves subjecting a butt welded, 50 mm thick plate to repeated blasts from high explosive while it is positioned over an annular-shaped die block.

In order to pass this test, the plate must develop a deep bulge, and sustain a specified reduction in thickness at a location close to the weld at the centre of the bulge. In the case of HY-80 steel, the specified minimum reduction is 16%. To qualify a given steel and weld, four such plates must achieve this reduction in thickness.

Because of the severity of the test, a number of mechanical tests and two "crack starter" tests may be performed prior to testing in order to establish that a candidate welded plate has a chance of passing. These tests are included in the present report.

The procedure to be followed for explosion bulge testing is specified in general terms in US Navy Specification NAVSHIPS 0900-005-5000 [3], although this specification alone is not sufficiently detailed for unambiguous conduct and interpretation of the test. Therefore, different testing authorities have developed their own detailed procedures for conducting the test. For example, in the US, NAVSEA-sponsored programs have established a detailed procedure which has been in use for a number of years [4]. The test procedure described in this report is generally similar to the NAVSEA procedure [4], but was developed independently and incorporates a number of features which are designed to suit the facilities at the proof range* available for testing, and to meet Australian safety requirements.

2.1 Test Procedure

The design of test plate is shown in Fig. 1. It consists of a 762 mm square, 50 mm thick plate having a double-vee butt weld across the centre. Composition and mechanical properties of the plate are given in Tables 1 and 2. The same heat of steel was used throughout this experimental program. The weld crown is ground for a distance of 150 mm from both edges of one surface so that the plate can sit flat on the die block during testing. This ground surface is referred to as the bottom surface. In addition, a 2 mm diameter by 25 mm deep hole is drilled in the centre of one side of each test plate (see Fig. 1) so that a thermocouple can be inserted into the plate at this location. It is usual to grind a short groove in the surface of the plate prior to drilling in order to remove a hardened region at the surface and assist in finding the hole during field testing. Present tests first used a close-fitting hole, but later plates incorporated a larger hole, counterbored 5 mm diameter to a depth of 20 mm, which was filled with silicone rubber to fix the thermocouple in place and seal it from weather which caused temperature readings to fluctuate.

As shown in Fig 1, four holes 25 mm in diameter are drilled through each corner of the test plate to accommodate temporary eye bolts for handling purposes.

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* Proof and Experimental Establishment, Graytown, Victoria

For the present application, welding of the plates is done by manual metal arc (MMA) using oven-dried electrodes. Preheat and interpass temperatures are kept below 150°C and no post weld heat treatment is used. During welding the plates are inspected visually and, in cases where the plate has cooled below 90°C, by magnetic particle inspection. The finished plate is inspected by radiography.

The die block for testing this thickness of plate is 100 mm thick, with an aperture 457 mm diam. blended smoothly into the top surface (Fig. 2). The present block was forged from 2.5% Ni Cr Mo gun steel to provide optimum strength and toughness.

The facilities for testing comprise this die block placed on a large 12 mm thick steel sheet on firm ground, a preparation area behind a concrete blast-proof wall located about 200 m from the blasting site, and splinter-proof viewing shelters located about 180 m from the blasting site. A thermocouple compensating lead extends from the blast site to the preparation area so that the temperature of the test plate can be monitored continuously.

Prior to testing the plate, a region of about 40 mm square adjacent to the weld and in the panel centre is ground smooth on both surfaces, to permit thickness readings to be taken both before and after testing by means of a special deep-throated thickness gauge. Such dressing is essential in order to remove mill scale and rust which might otherwise be dislodged by the blasting and lead to spurious results.

An expendable thermocouple lead is then fed into the small hole in the side of the plate and sealed in place using silicone rubber.

Testing is conducted at - 17.8°C (0°F). To cool the plate, temporary eye-bolts are fixed to each of the corner holes in the test plate. It is then lifted by mobile crane and positioned in an insulated box for cooling to a temperature of about - 50°C. Cooling (Fig. 3) is achieved by pumping liquid nitrogen into the base of the box for sufficient time (about 20 minutes) to create a liquid pool about 5 mm deep. After this, evaporative cooling brings the plate to an undercooled temperature. Temperature in the box is monitored by thermocouples at four locations: the first is at the base of the box and reads approximately minus 180°C so long as liquid nitrogen remains there; a second thermocouple is fixed into the side hole of the plate; and the remaining two thermocouples are held in contact with the top of the plate by a small weight. Continuous temperture recording of the thermocouple outputs is provided by a multi-pen chart recorder. The temperature of the plate is considered stable when all of the thermocouples read the same temperature to within 5°C. The complete cooling cycle takes typically 1.5 to 3 hours.

When it has stabilized at the appropriate undershot temperature, the plate is removed from the cooling box and is transported to the die block by a mobile crane equipped with four lifting hooks. Upon reaching the die block the plate is positioned squarely on it and the thermocouple wire is plugged into the compensating lead. From this moment on, the temperature of the plate is monitored remotely by the chart recorder located at the preparation area.

The eye-bolts are then removed (to avoid destruction by the blast) and the appropriate charge is placed on a small, flimsy table to achieve the specified stand-off distance of 381 mm above the lower face of the test plate*. Central location over the plate is achieved by locating the four legs of the table on diagonal lines marked across the plate (see Fig. 4).

The warming rate of the test plate is characteristically very rapid while the plate is being transported to the die block and for a short time thereafter. During this period the plate usually develops a thick frost which acts as a very efficient temperature buffer, causing the warming rate to slow to a steady value of about 0.5°C/min. This very slow rate of temperature rise allows ample time for temperature equilibration throughout the bulk of the plate, and the reading of the single inserted thermocouple provides a reliable indication. The explosive charge is detonated when the temperature recorded in the plate passes through minus 17.8°C. Since both the thermocouple and compensating lead are calibrated, this temperature is considered to be accurate to within ± 0.5°C.

After the blast, the test plate is returned to the preparation area for examination and assessment.

2.2 Plate Assessment

The first step is to closely inspect both surfaces and record the location, length and direction of any cracks. The plate is then photographed from a direction looking along the plane of the plate so that the profile of the bulge can be recorded. Photographs of both plate surfaces and of any cracks are also taken.

The depth of bulge is determined by placing a straight edge across the plate from the centre of one side to the centre of the other. The distance is then measured vertically down from the base of this straight edge to a position adjacent to the weld at the lowest part of the bulge. The procedure is repeated with the straight edge placed at right angles, and the two bulge depth figures are then averaged.

The reduced plate thickness is measured by taking a number of micrometer measurements in the cleaned area of the plate. Reduction in thickness is then given by $(t_i - t_r)/t_i$ where t_i is the initial thickness and t_r is the reduced thickness.

Assessment of the actual plate condition is based upon the following criteria:

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* Measured at the start of testing, before bulging occurs.

(i) If no cracks exist but insufficient reduction in thickness had been obtained, the plate is returned to the cooling bath for additional testing.

(ii) Failure occurs if cracking enters the hold down region (see Fig. 5) of the plate and the required 16 percent reduction in thickness has not been achieved. Additionally, no fragments are to be thrown out of the test specimen.

(iii) Success occurs if the plate achieves a 16 percent reduction in thickness (with or without minor cracking) at a location adjacent to the weld, ie about 10 mm distant from the weld toe.

(iv) If minor cracking exists, and the plate has not achieved the required 16 percent reduction in thickness, subsequent action is determined by the scientific officer in charge of the testing program.

3. FIRST SERIES OF TESTS

The first plates to be tested were prepared by Williamstown Naval Dockyard. Plate preparation and weld procedure followed that specified in reference 5, using 4 mm diameter, Lincoln type AWS E 11018-M electrodes.

All four plates were radiographed and found to be free from crack-like defects; however they contained a number of small regions of fine porosity associated with re-starting of electrodes. Such porosity was considered not to detract from the performance of the plate under explosion bulge testing (Crack-starter plates were not prepared).

The plates were tested during the period 9-19 May 1983 and, as shown in Table 3, all failed to achieve the required 16% reduction in thickness. In fact, the greatest reduction in thickness achieved was 8.4%.

A summary of the results provided by tensile testing (to ASTM E8-81) on the first series of test plates is given in Table 4, and the Charpy transition curve (to ASTM E23-81), in Fig. 6. The results of transverse tensile tests on weldments have limited significance because the actual fractures occurred in the parent metal away from the welds. Therefore no measure of weld metal tensile properties was obtained other than an indication that the yield and tensile strength exceeded those of the parent metal. From a practical viewpoint, the high strength of the weld zone caused deformation, and subsequent failure, to be concentrated in the adjacent parent metal. It could therefore be anticipated that high weld metal strength in the explosion bulge test plate would be a distinct disadvantage in leading to premature failure of the plate.

In view of the explosion bulge test failures occurring so readily in the weldments, the Charpy impact properties given by Fig. 6 clearly fall short of the exceptionally high level required to withstand the explosion bulge sequence. This matter is discussed later in detail (section 5).

Side bend tests (to ANSI/AWS-B4.0) were conducted on welded plate taken from the first series of explosion bulge tests, however these were found to be of limited value in predicting the performance of the test plate since the specimens passed easily.

Detailed examination of the fractured test plates showed that all four followed a similar pattern, with the fracture faces having a similar appearance. In all cases cracking initiated in the weld near the centre of the plate and the fracture consisted of a main crack following an irregular path through the weldment. Along the weld the crack tended to follow the interface between weld runs and occasionally crossed one or more runs before resuming its longitudinal course. This cracking was essentially "square" in appearance; that is, it was relatively flat and normal to the surface of the plate, and produced negligible shear lips at the surface. These macroscopic features are indicative of low ductility failure. In the through- thickness direction (Fig. 7) the crack was largely insensitive to microstructure although there was some tendency for cracking to seek out the fusion boundaries between adjacent welds and between the weld and parent metal. In addition, cracks travelled through some welds by going down the columnar grain boundaries. Under scanning electron microscopy, cracks which travelled in the through-thickness direction exhibited shallow microvoid coalescence, again indicative of limited ductility.

By contrast, the linking cracks (which travelled along a plate parallel to the plate surface) were more slanted, and SEM examination showed greater deformation in the microvoids, suggesting a greater degree of ductility in the fracture mode.

This evidence points to crack propagation occurring by tensile overload with very low ductility linked by a series of steps having a more ductile, shearing failure mode.

By contrast, cracking which extended into the parent metal developed an almost fully slant fracture mode, indicative of stable ductile tearing by a shear mechanism. Follow-up explosions caused relatively small extensions to these cracks, and none of the cracks in the parent plate extended outside the bulge zone. From these observations it was concluded that the parent plate is highly resistant to crack propagation and exhibits a stable, ductile fracture mode.

There was negligible evidence of cracking, or the formation of cracklike defects, in the weld existing prior to the explosion bulge testing.

The weld section (Fig. 7) shows that the individual weld passes were to some extent randomly located and that individual weld deposits varied considerably in size. The microstructural grain size varied from pass to pass, although it tended to be consistently small; these observations indicate that the heat input of welding during deposition of the passes had been varied considerably.

Hardness measurements taken at a number of locations across the weld, indicated a hardness range from 290 to 350 HV, the hardest region being in weld metal HAZ close to the surface. These hardness values are indicative of a yield strength of 730-870 MPa [7] compared with the specified range of 680-700 MPa for the electrodes used. That is, the hardness and strength of the as-deposited Lincoln E 11018 M weld metal was very high, a cause for concern because high hardness is usually accompanied by low toughness at sub-zero temperatures. The excessive hardness also suggests that an unduly high heat input and incorrect welding sequence may have been used. (See later, Section 5.1).

Because failure of this first series of plates was caused by unsatisfactory weld metal properties, these tests actually did not test the parent plate. This could only be achieved by raising the weld metal properties to the level of surviving the explosion bulge test. There was a clear need to conduct a detailed evaluation of alternative welding consumables and to experiment with welding procedures so that the optimum weld properties could be provided for future tests.

4. TESTING OF UNWELDED PLATE

The results of this first series testing program were discussed at a meeting of representatives from Industry Development Branch (IDB; NSW & Canberra) Williamstown Naval Dockyard (WND), Director of Naval Quality Assurance (DNQA) and MRL at Williamstown Naval Dockyard on 8 June, 1983. As a consequence of this meeting, MRL was tasked by IDB to undertake a study of the alternative welding consumables and procedures so that a second attempt to pass the explosion bulge test could be made.

Before proceeding with this investigation, however, it was necessary to obtain quantitative information about the strains developed during the course of a test. It was also considered essential to demonstrate that the parent plate intrinsically had adequate toughness and ductility to survive and pass an explosion bulge test series. For these reasons a standard size test plate was prepared from the same heat of steel and subjected to a test program of five blasts. One face (to be the bottom in the explosion bulge tests) was painted and a 21 mm orthogonal grid was scribed for the purpose of strain measurement.

The plate surpassed test requirements, reaching 25.8% reduction in thickness near the peak of the bulge without any cracking.

Measurements of strain were made across various spans, equidistant about the bulge centre, so that the accumulated plastic strain across the plate could be established after each blast. The number of measurements was limited in later stages of the test by physical obliteration of the grid. The surface strains are recorded in Fig. 8, and tracings taken from photographs of the bulge are shown in Fig. 9.

It is noted that the measuring technique gave values of strain averaged across a particular span and not the specific strain at any point. The strain at the centre of the bulge was determined by extrapolation of the curves to the point of zero span, and so represents the actual value of peak strain.

The relationship between biaxial <u>surface</u> strains (ε_x, ε_y) and through-thickness strain (ε_z) as bulging developed is shown in Fig. 10. While this relationship is non-linear at values of strain up to about 10%, there is clear indication of larger strains approaching a linear relationship having a slope of 2, the value expected for balanced, purely biaxial plasticity.

The reason for this non-linearity is that, in this geometrically thick plate, the bulging deformation deviates markedly from that of a pure membrane, and bending strains dominate the initial deformation. Thus, on the convex face (measured in these tests) the tensile membrane strains ε_x and ε_y are greatly augmented by the tensile strain from bending, apparent in Fig. 10. To balance out, the strains on the concave face would have been dominated by a compressive bending strain. As the bulge develops, the membrane strains increasingly dominate the deformation, so that the relationship with ε_z approaches the purely biaxial case.

It can be seen from Fig. 10 that, for a reduction in thickness (ε_z) of 16%, the plate bottom surface is required to undergo strains (ε_x, ε_y) of about 18%. In the first series of explosion bulge tests the plate survived no more than 2.5% reduction in thickness before the next successive blast caused failure. For the unwelded plate, 2.5% thinning corresponds to a biaxial strain of 6%.

Tensile testing on weld metal removed from the first series of explosion bulge plates gave a value of elongation to fracture of 17.5%, (Table 4), so that ductility considerably in excess of this level is required for welded plates to pass the explosion bulge test. The plate mechanical properties (Table 2), in particular the elongation values of 23% and 24% at room temperature and to a lesser extent the Charpy impact energy in excess of 140J at -85°C provide an indication of the benchmark values of elongation and toughness required of deposited weld metal to comfortably pass the explosion bulge test.

It is important to note that the deformation during bulging varied smoothly across the span of the plate to within narrow limits. This was not the case when testing the first series of welded plates, where the greatly overmatching strength of the as-deposited weld metal and of the parent heat-affected zone are known to introduce large variations in local stain at different points across the weld and along it. From limited measurements available [8], use of a weld filler metal of roughly matching strength may sustain strains approaching twice the average strain*, while the flanking parent heat-affected zone material hardly deforms at all. With weld metal of overmatching strength, the local strains thrown onto the parent material flanking the weld are likely to be very much greater than the uniform strain, although the precise amount of strain concentration remains unknown. A considerable margin of safety is therefore required in the parent metal properties to cope with this redistribution of strain.

More importantly, still higher levels of elongation and dynamic fracture toughness are required of the weld metal, to cope with unknown peaks in localized strain caused by the presence of the heat affected zone, and by microstructural variations intrinsic to the multipass welds.

5. EVALUATION OF WELDING CONSUMABLES

This study was undertaken in order to obtain a weld metal deposit and multipass welding sequence which would give satisfactory performance in the explosion bulge test. The work was limited to a laboratory evaluation of those properties considered to give a reliable indication of explosion bulge performance. These properties were:

(i) ductility, as given by elongation to failure in a tensile test at minus 17.8°C, the explosion bulge test temperature;

(ii) Charpy V-notch impact energy at temperatures centred around minus 17.8°C;

(iii) microstructure; and

(iv) dynamic tear toughness. This test was restricted to the selected consumable, as a further indicator of likely performance in the explosion bulge test.

A total of nine electrodes were selected; three from the United States, four from Europe and two from Australia. All electrodes were 4 mm diameter, low-hydrogen types with basic flux coatings.

As-deposited weld metal for testing was obtained from double-vee butt welds made in 32 mm thick HY-80 plate. The welding procedure was developed as a prototype for the detailed procedure for the 50 mm thick explosion bulge test plates (see Section 6). Some minor procedural alterations were undertaken during the welding of successive plates, but these were not sufficient to negate direct comparison of weld metal test samples. A

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* Average strain at a given location on the bulge, determined by tests on unwelded plate.

check on consistency was made by repeating the first candidate electrode later on in the series.

All plates were radiographed upon completion of welding. Apart from traces of fine porosity, all were clear of defects and considered acceptable for the extraction of test specimens. Chemical analyses of deposited weld metal samples, taken from the central parts of the weld and therefore essentially free from plate dilution effects, are given in Table 5.

5.1 Tensile Tests

Tensile test specimens were wholly in the weld metal, cut from both the top and the bottom of the weld, and oriented in the weld longitudinal direction. Tensile tests were conducted in accordance with ASTM E8-81, at minus 18°C so that the properties obtained would relate directly to the explosion bulge test temperature. Test results are summarized in Table 6.

The important values of elongation of the weld samples are presented graphically in Fig. 11. This evaluation takes into account an interpretation of tensile fractures involving an upward adjustment of elongation values to compensate for fractures occurring outside the middle third of gauge length, when the proximity of specimen shoulder restricted tensile elongation. The conservative correction to elongation, based on extensive experience, is + 1% for such steels.

Additional upward corrections are made for cases where optical examination of the fracture revealed the presence of weld porosity which clearly initiated premature fracture. This effect occurs after the ultimate tensile strength and point of plastic instability, and therefore only limits the elongation and reduction of area values. Corrections take account of both fracture appearance and extent of porosity, and are of the order of +0.5% for slight porosity to +1% for moderate*. These corrections again are considered to err on the safe side. Specimens showing more severe porosity were discarded from the evaluation.

The critical benchmark level of elongation and the band above it (Fig. 11) represent the minimum level of elongation which must be reached for a weldment of good quality parent HY-80 plate to have a tolerable chance of passing the explosion bulge test. The benchmark was arrived at from a consideration of the performance of previous plates (discussed in Section 3) and after consultation with Alm [6] to obtain the benefit of long experience in the explosion bulge testing of HY-80 plate.

From Fig. 11 it is seen that only one electrode, Philips 10018, easily exceeded the benchmark value.

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* Approximately 5% and 10% respectively of the cross-sectional area.

5.2 Charpy Impact Tests

Charpy V-notch impact specimens were cut transversely to the weld, and within 3 mm of the weld surface, with the notch normal to the weld surface. In this way, the notch sampled several passes simultaneously as the fracture ran along the weld, so giving an averaging effect.

Charpy specimens were taken from the bottom weld only, because of the possibility of strain ageing occurring in the top (i.e. first) weld. The Charpy tests were done in accordance with ASTM E23-81, using specimens in triplicate wherever possible at temperatures of -40°C, -18°C and 0°C. The ASTM profile of striker was used to allow direct comparison of results with data from the US.

The Charpy V-notch test results are recorded directly in Fig 12. The benchmark is again drawn from experience with the first series of explosion bulge trials and from US experience [6].

It can be seen from Fig. 12 that two electrodes are clearly outstanding: Fortrex 11018 and Philips 10018. Both of these give exceedingly high values of impact energy for as-deposited weld metal, for temperatures of minus 18°C and above. An undesirable feature of the Fortrex 11018 is that the impact energy falls away rapidly below minus 18°C; the shift in transition curve to higher temperatures with the increased strain rate of explosive loading would therefore markedly erode the toughness at -18°C. This trend is not present with the Philips 10018 weld metal, which retains high toughness values even at -40°C, and suggest that explosively loading would have little influence on effective toughness at -18°C. It is therefore possible to single out the Philips 10018 electrode as having Charpy impact values well in excess of the benchmark along with a very desirable trend with temperature.

The Charpy values for the Atom Arc T electrodes used in two separate plates give an indication of the good reproducibility of properties from separate welds (Fig. 12).

5.3 Dynamic Tear Tests

The specification for dynamic tear testing is provided in ANSI/AWS-B 4.0 combined with ASTM E604. The object of the test is to drop a tup of known weight and height onto the back of a notched test specimen and determine the energy absorbed up to the point of complete fracture. In principle the test used here is similar to the Charpy impact test, with two exceptions:

(i) The test plate is much larger (14 mm wide x 38 mm deep) so that a larger volume of weld metal is sampled. This is essential for the testing of welds because impact properties can vary considerably across a multipass weld section.

(ii) Because an instrumented drop tower was not available, the test was conducted on a go/no go basis at different predetermined energy levels in the tup.

Results from the dynamic tear tests on Philips 10018 weld metal indicated that the energy to fracture at -29°C exceeded 678 J, and would be in the order of 680-740 J, which compares favourably with the benchmark value of 600 J at this temperature [6].

5.4 Weld Metal Microstructure

The microstructure of the as-deposited metal in multi-pass welds such as the present depends primarily on the composition of the electrode and flux coating, and is affected to some degree by the welding conditions and by the tempering effects of subsequent weld passes. All of the weld metal samples examined had microstructures which fell within the limits regarded as acceptable in view of the mechanical properties required. The as-deposited weld metals formed columnar grain structures, the grains comprising a varying, complex mixture of fine acicular ferrite and bainite. All contained small amounts of proeutectoid ferrite on the grain boundaries, and some had considerable development of ferrite side plates extending into the grains.

In the Philips 10018 weld metal the amount of proeutectoid ferrite was noticeably limited, and there were just a few areas of restricted side plate development (Fig. 13). Higher toughness properties are generally associated with minimum amounts of ferrite in these grain boundary and side-plate forms. The tempered zones of weld metal consisted essentially of fine grained acircular ferrite. This microstructure is considered to offer the highest level of notch toughness, essential in explosion bulge testing. Some areas of very fine structure, probably carbide-rich, remained unresolved.

Of all the electrodes tested in the present work the Philips 10018 electrodes were identified by the tradesman welder as being easiest to deposit, having particularly free flowing characteristics and giving very little spatter.

Overall, these results showed that only the Philips 10018 electrode met the benchmark requirements so that, given a sound welding procedure for the purpose, there was every reason to believe that such a weld would survive the explosion bulge test.

It is noted that the chemical composition of weld metal deposited from the Philips 10018 electrode (Table 5) complies with the requirements of MIL-10018-M, MIL-10018-M and of MIL-10018-M1. The mechanical properties (Table 7) satisfy all three, with one exception - the yield and tensile strength do not meet 11018-M, which is considered to represent an undesirably high degree of overmatching of weld metal strength relative to the parent plate.

Most importantly, the yield strength of the Philips 10018 metal falls within the range of the drastically revised MIL-10018-M1 type for welding HY-80, and the ductility, Charpy impact toughness and dynamic tear toughness all surpass the M1 requirements by considerable margins. This classification has recently been the subject of development work sponsored by NAVSEA with the aim of establishing an electrode formulation which offers real chance of making the explosion bulge test work for HY-80 steel welded by manual metal arc [6]. One electrode has recently been tested and found to satisfy the requirements of 10018-M1 and adequately passed a trial explosion bulge test series [6]. The Philips 10018 electrode is notably similar to this developmental electrode, possessing generally similar chemical composition, strength and dynamic tear toughness, but offering significantly higher values of ductility and Charpy toughness. Therefore, given a sound welding procedure for the purpose, the Philips 10018 electrode offers a very strong prospect of performing successfully the explosion bulge test, and so enabling a valid assessment to be made of locally-produced HY-80 steel plate.

6. DEVELOPMENT OF WELDING PROCEDURE

In addition to finding a suitable electrode, it was particularly important to devise a welding procedure which would achieve the optimum combination of strength, ductility and toughness of the complete weldment under explosion bulge testing.

The specification for explosion bulge testing [3] places a number of restrictions on the welding procedures that may be used. These include :

1. a maximum preheat and interpass temperature of 150°C;
2. no post weld heat treatment;
3. a maximum heat input of 2.15 kJ per mm; and
4. no dressing of the weld surface.

In addition, there are standard techniques, consistent with good welding practice, which improve the toughness of a joint. These include:

1. The heat input is kept as low as possible. This provides small welds beads having a small grain size. In particular:

   (a) "Stringer bead" technique is used for all passes except the root run. The technique involves welding along a straight line at the fastest practicable travel speed while ensuring complete fusion.

   (b) Currents are kept low so that the weld depth/width ratio is a minimum.

2. The welding sequence is chosen so that, as nearly as possible, each weld pass travels along the toes of preceding welds. This practice melts the hard, inherently crack-sensitive heat affected zone at the weld toe and tempers the heat affected zone adjacent to the toe.

3. At each layer of weld metal the welding sequence progresses from the sides of the joint (i.e. the parent metal) towards the centre. This is done

to ensure that the most sensitive heat affected zone, in the parent metal, receives the maximum benefit from tempering by the succeeding passes.

4. The weld crown is kept as low as possible, i.e. with minimum reinforcement, so that the weld deformation is as close as possible to being uniform with the parent plate.

In this work an additional technique has been employed to improve the performance of the joint. It has been recognized that the most sensitive part of the weld is the heat affected zone flanking the two extreme weld capping passes on the surface of the plate. These zones:

(i) cannot be removed or tempered by subsequent weld passes;

(ii) occur in a region where the maximum tensile strains in the joint are experienced;

(iii) exist in a location where weld defects such as undercut and hydrogen cracking are most likely to occur.

Since these two zones cannot be removed other than by completely re-heat treating the plate, it was decided to position the two extreme capping passes in a region where their influence would be least harmful. This was done by locating them some 8 mm beyond the edge of the joint preparation, as shown in Fig. 14 (beads 19 and 20, 52 and 53). A "top-hat" profile was thus obtained.

The underlying philosophy is that any crack starting at the weld toe must travel almost parallel to the plate surface for some distance if it is to reach the inherently brittle heat affected zone along the side of the joint proper and so cause a serious cracking problem. Since this fracture path is almost parallel with the applied stress it represents an energetically unfavourable path. The onset of cracking is therefore likely to be delayed until more extensive bulging occurs. Alternatively, if the initial toe crack does not turn but instead propagates directly into the plate as favoured by the explosive loading stresses, it runs immediately into sound parent plate whose crack-arresting properties were shown to be very high. Again, cracking deeper than the surface weld bead would be delayed until extensive bulging had occurred.

It should be noted that the joint design shown in Fig. 14 also has a weld deposited over each of the capping passes at the side of the joint (runs 21 and 22, 54 and 55). These welds are deposited with the arc directed at the edge of the original joint preparation and their purpose is to temper the inside toe of the edge capping passes. The final weld pass, which cannot be tempered by a subsequent pass, is in the centre of the weld in order to be furthest possible from the harmful toe regions (passes 27 and 60 in Fig. 14).

7. SECOND SERIES OF TESTS

7.1 Preliminary Mechanical Tests

Prior to conducting the explosion bulge trial the specification [3] requires a number laboratory mechanical tests to be conducted on the 50 mm thick plate welded by the same procedure as the explosion bulge test plates. The tests required are side bend, Charpy V-notch and tensile tests.

In addition to these mechanical tests, two crack starter explosion bulge tests are required to be conducted on welded plate. The crack starter plates are similar to the explosion bulge plates except that beads of hard facing deposit are laid on the weld surface as shown in Fig. 1. The test was designed to initiate running cracks in the weld, and so provide a measure of crack arresting properties of the parent plate.

In view of the unproven field performance of this weld procedure and the Philips consumable, the second test program was pursued step-by-step. The dynamic tear test was added to the requisite mechanical tests, and crack-starter plates and explosion bulge plates were fabricated only when the preceding stage of testing was cleared. In this way substandard materials or welds could be identified at the earliest stage. The benchmark properties were those determined from the electrode evaluation studies (Section 5) and from Alm [6]. All of the mechanical test results are summarized in Table 8.

All test specimens were removed from the welded test plate as shown in Fig. 15. Tensile tests were conducted at -18°C on metal removed from both across and along the weld. Results are given in Table 8. The longitudinal elongation values of 26 and 27% exceed the benchmark requirement given in Fig. 11 and indicate that adequate ductility has been achieved in the final plates. The transverse test specimens gave values of 22 and 23%. These are equal to parent plate values under similar conditions and, since the unwelded plate easily passed the explosion bulge test, are indicative of adequate transverse ductility.

Charpy V-notch impact specimens were removed from the weld as shown in Fig. 15. The notch on each specimen was located in the centre of the weld along a direction perpendicular to the plate surface. Specimens were removed from both top and bottom welds at a location as close as practicable to the plate surfaces. Results, presented as a transition curve in Fig. 16, reveal adequate impact toughness at temperatures close to the test temperature (-17.8°C) in comparison with the benchmark curve (Fig. 12).

It is noted that in Fig. 16 the transition to brittle behaviour occurs at temperatures between -60 and -40°C, which is somewhat higher than the temperature range of Charpy values from the 32 mm thick plates used for the consumable evaluation (Fig. 12). Nevertheless, the result was considered adequate to proceed with the experimental program.

To provide additional information about the notch toughness of the welded joint, dynamic tear tests were made on specimens removed from both the weld and parent metal. Results of all dynamic tear tests at -28°C (Table 8) indicated that the weld had a dynamic crack toughness energy in excess of 636J, based on a failure criteria of complete fracture. This level was not as high as obtained with the 32 mm thick plate, but comfortably exceeded the benchmark value of 600 J quoted by Alm.

Side bend tests on the welded plate, again proved to be of limited value since, as with the first series of tests, they passed easily.

7.2 Explosion Bulge Testing

The second series of explosion bulge tests was conducted at P & EE, Graytown, over the period 13 February to 6 April, 1984. Results are summarised in Table 9.

The first two tests were crack starter tests, welded by Williamstown Naval Dockyward under supervision of MRL officers. It is normal to subject these plates to two blasts; the first is intended to initiate a small crack, while the second causes the cracks to extend rapidly into the parent plate and so provide an indication of the crack-arrest properties of the test plate.

Both crack starter plates passed easily. The first plate achieved a reduction in thickness of 9.3%, which compared favourably with the minimum requirement of 6%, and is greater than the best result achieved for the first series of explosion bulge tests [8.4%]. This plate was then subjected to an additional blast for curiosity sake because the extent of cracking was exceptionally small. This final blast produced extensive through-thickness cracking but the plate still passed according to specification and achieved a reduction in thickness of 13.4%, an exceptionally large value for a crack starter plate.

The second crack starter plate passed easily, with a reduction in thickness of 7.5% after the second blast.

Having satisfied the required standard for crack starter testing, four explosion bulge plates were welded without any change to the procedure, and subjected to explosion bulge testing. All plates passed easily, as described below.

The first plate was subjected to five blasts and achieved a total reduction in thickness of 29.9%. At this stage the plate contained one through-thickness crack along the weld and three cracks in the parent metal (Fig. 17). Since none of these cracks extended beyond the circle of contact between the test plate and die block at the moment of blasting, the plate still satisfied the specification requirements [3]. The reduction in thickness (29.9%) compares very favourably with the specified minimum of 16%.

The second plate achieved a reduction in thickness of 18% after four blasts. The plate surface (Fig. 18) showed minor cracking at the fusion boundary, the junction between the heat affected zone (HAZ) and the parent metal, and two short cracks between adjacent capping passes on the weld crown.

The third plate was subjected to five blasts and achieved a total reduction in thickness of 24% (Fig. 19). The plate showed cracking at both weld toes and some cracking along the junction between the HAZ and the parent metal. One crack occurred across the weld and two short cracks appeared between adjacent capping passes. None of these cracks was through-thickness and none came close to the ring marking the hold-down location of the die block.

The fourth plate (Fig. 20) achieved 25.7% reduction in thickness after 5 blasts. The plate exhibited three weld metal cracks about 40, 30 and 25 mm in length respectively. The first two of these cracks grew slightly into parent metal. There was also some minor cracking along the fusion boundary.

The results achieved in the second series of trials were almost twice the test requirement and represent more than a three-fold improvement over the results from the first trial.

To assess the influence of the top-hat weld design on performance of the test plates, a section across the weld was removed from the third test plate. This showed that cracking which initiated at the weld toe travelled straight into ductile parent metal and developed a fully slant fracture mode (Fig. 21). This is evidence that the top-hat design contributed significantly to the satisfactory performance of the test.

The results of second series explosion bulge testing (Table 9) showed a progression in bulge depth and plate thinning after each blast similar to that achieved for the unwelded plate (Fig 9). This indicates that the ductility of the weld zone under explosive loading is similar to that of the unwelded parent metal.

8. SUMMARY AND CONCLUSIONS

1. Test plates welded under normal fabrication shop conditions, using AWS E 11018 M electrodes and procedure specified by NAVSHIPS 0900-005-5000 (1965), failed to pass the explosion bulge test because excessive hardness and inadequate toughness and ductility in the weld metal led to early failure through the weld.

2. Failures in the first series of explosion bulge tests occurred at half or less than the specified 16% thinning at the bulge apex. Fracture in the weld metal was essentially brittle. Cracks running into the parent plate developed an almost fully slant, ductile mode, and extended little during

follow-up explosions: evidence of a high level of fracture toughness in the unwelded plate.

3. An unwelded test plate performed exceptionally well during explosion bulge testing, reaching 25.8% reduction in thickness without sign of cracking, and with a uniform pattern of bulge deformation.

4. Examination of a wide range of low hydrogen electrodes appropriate to welding HY-80 steel by the MMA process revealed that one electrode, Philips 10018 type complying with AWS E 10018-M, from which the as-deposited weld metal satisfied benchmark values of both ductility and Charpy impact toughness necessary to have a worthwhile chance of passing the explosion bulge test. Dynamic tear toughness was also sufficient in this regard. Respective values were 27-30% elongation on 4 diam. gauge length, 103-112 Joule CVN at -18°C, and 670-740 Joule dynamic tear energy at -29°C.

5. A welding procedure was prepared for fabricating the HY-80 steel plate in order to achieve maximum weld metal toughness and greatest resistance to the propagation of any surface cracks into the welded joint. It uses stringer bead technique with limited heat input, and tempering of all passes except for the toes and central pass of the capping layer. A "top-hat" profile ensured that the untempered toe runs were less likely to cause through-thickness cracking.

6. Using the Philips 10018 welding electrodes and revised top-hat welding procedure in the fabrication of a second series of explosion bulge test panels led to a completely successful outcome in the explosion tests. The two pre-notched crack-starter panels and the four bulge test panels all passed with large margins, achieving up to twice the specified thinning in the bulge.

7. Together with the high levels of mechanical test properties, this outcome of the explosion bulge testing established that the HY-80 steel plate (BIS Heat No. 2K07030) easily satisfied all the requirements for first article mechanical testing as specified in MIL-S-16216 H (SHIPS) and also the revision MIL-S-16216J (SHIPS).

9. ACKNOWLEDGEMENTS

The authors acknowledge the vital assistance given by Army Q.A. Division (Proof and Experimental Group) in making available the Graytown Establishment. They also provided hospitality, manpower resources and equipment during the explosion bulge trials. H.M. Naval Dockyard Williamstown freely made available production welding facilities and supplied skilled welders for laboratory experimental welding undertaken at MRL. Gavin Ryan is thanked for his major effort in supervising both explosion bulge trials at Graytown and the welding of test plates at Williamstown Dockyard.

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6. Alm, R.D. (Head of Welding Engineering Division, Mare Island Naval Shipyard, Vallejo, Ca, USA), Private communications.

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TABLE 1. CHEMICAL ANALYSIS OF HY-80 STEEL PLATE

Element	Bunge Heat No. 2K0 7030	MIL-S-16216H (SHIPS)
C	0.135	0.10-0.20
Mn	0.17	0.10-0.45
Si	0.19	0.12-0.38
S	0.014	0.025 max
P	0.019	0.025 max
Ni	2.70	1.93-3.32
Cr	1.35	0.94-1.86
Mo	0.48	0.17-0.63
V	0.006	0.03 max
Ti	0.002	0.02 max
Cu	0.023	0.025 max
Al	0.045	
Sn	<0.002	
Ca	0.0012	

Analyses are in weight percent and refer to the final solid product.

TABLE 2. MECHANICAL PROPERTIES OF HY-80 STEEL PLATE UNDER INVESTIGATION

Property	Bunge heat No. 2K07030 Top of plate	bottom	MIL-S-16216H (SHIPS)
0.2% proof Stress (MPa)	620	633	552-655
UTS (MPa)	748	753	to be recorded
Elongation on 50 mm g.l. (%)	23	24	20 min
Redn of area	69	69	50 min
Charpy V-notch impact energy (J at -85°C)	157, 159, 168	141, 143 149	68 min

TABLE 3. RESULTS OF FIRST SERIES OF EXPLOSION BULGE TESTS

Test No.	Test temp. (°C)	Charge weight (kg)	Result	Accumulated Bulge depth (mm)	Accumulated Thinning * (%)
			Plate 1.		
1	-17.3	11	no cracks	31.5	2.0
2	-10 †	14	cracks	73	7.0
3	-17.9	12	cracks within bulge region in plate, to edge of bulge in weld.		
			Plate 2.		
1	-17.9	12	no cracks	33.5	1.9
2	-18.1	13	no cracks	66	5.9
3	-17.9	13	cracks outside bulge region along weld, no cracks in parent plate. Plate split.		8.4
			Plate 3.		
1	-17.8	13	no cracks	37	2.4
2	-18.1	12	cracks	76	4.9
3	-17.9	13	cracks within bulge region in weld and plate.		
			Plate 4.		
1	-17.2	13	cracks	42.5	2.7
2	-18.1	13	cracks within bulge region in plate.	≈ 100	6.1

* Accumulated reduction in thickness at bulge centre.
Error ± 0.25%.

† Estimated. Problems with temperature measurement on die block.

TABLE 4. TENSILE PROPERTIES OF WELDS USED IN THE FIRST SERIES OF TESTS

	Specimen	Test Temp. (°C)	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation on 4 dia. (%)	Redn area (%)
1)	Transverse,	20	625	723	17†	74†
2)	containing	20	624	724	18†	74†
3)	weld*	20	629	732	18†	74†
4)	Longitudinal	20	780	885	17.5	61
5)		-17.8	863	894	21	68.5

* Specified by NAVSHIPS 0900-005-5000 (1965).

† All three specimens failed outside the gauge length, in the lower strength parent rather than in the weld metal.

TABLE 5. CHEMICAL ANALYSES OF EXPERIMENTAL WELD DEPOSIT SAMPLES

Consumable	Analysis (weight percent)										
	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	B	V
Atom Arc T	0.10	1.51	0.31	0.008	0.018	1.9	0.49	0.37	0.06	0.007	0.005
Fortrex 11018	0.06	1.71	0.32	0.006	0.013	1.8	0.15	0.40	0.02	-	0.026
Lincoln 11018	0.09	1.50	0.50	0.009	0.012	2.2	0.13	0.39	0.02	-	0.010
Philips 11018	0.09	1.60	0.43	0.008	0.020	2.1	0.17	0.42	0.02	-	0.016
CIG 11018	0.07	1.54	0.38	0.009	0.022	2.3	0.32	0.42	0.02	-	0.024
Philips 10018	0.08	1.24	0.44	0.007	0.013	2.1	0.13	0.40	0.02	-	0.017
WIA 11018	0.08	1.81	0.30	0.009	0.024	2.1	0.34	0.39	0.02	-	0.014
Fortrex B	0.06	0.93	0.34	0.008	0.014	1.4	0.64	0.27	0.05	-	0.004
Airco 11018	0.08	1.43	0.44	0.013	0.011	2.1	0.31	0.38	0.03	-	0.003

All samples: Nb < 0.006
Al ≤ 0.002

CIG = Commonwealth Industrial Gases P/L, Australia.
WIA = Welding Industries of Australia.

TABLE 6. TENSILE TESTS ON EXPERIMENTAL AS-DEPOSITED WELD METAL (-18°C)

Electrode		Yield Stress (MPa)	Tensile Strength (MPa)	Elongation on 4 dia. (%)	Redn. area (%)	Comment Fracture location	Porosity
Atom Arc T	(T)	*695	905	22	62	CT	clear
Bottom weld	(B)	*855	900	19	64	CT	trace
Fortrex 11018	T	735	820	23	69	OMT	trace
	B	835	850	20	56	OMT	marked
Lincoln 11018	T	*738	880	23	63	CT	marked
	B	755	885	25	66	CT	clear
repeat	B	795	870	24	67	CT	clear
Philips 11018	T	745	895	22	62	CT DISCARD	bad
repeat	T	710	885	28	68	CT	clear
	B	*820	865	24	67	CT	trace
CIG 11018	T	710	890	22	66	CT	trace
repeat	T	755	885	25	66	OMT	clear
	B	825	890	24	64	OMT	mild
Philips 10018	T	670	805	27	68	OMT	trace
	B	700	775	29	69	OMT	clear
WIA 11018	T	820	905	21	62	OMT	trace
	B	845	901	23	65	CT	clear
Atom Arc T	T	750	925	24	66	CT	clear
(check)	B	865	920	13	31	OMT DISCARD	bad
Fortrex B	T	680	775	24	67	OMT	mild
repeat	T	670	760	27	70	CT	trace
	B	740	795	23	67	OMT	mild
Airco 11018	T	740	860	27	67	CT	clear
	B	809	864	24	54	OMT	trace
MIL-E-22200/1F Grade 11018-M		676 - 758	758 min	20 min	-		

All tests done at -18°C.

Fractures: CT = inside centre third of gauge length
OMT = outside middle third

* No sharp yield point, value represents 0.1% proof stress.

TABLE 7. MECHANICAL PROPERTIES OF PHILIPS 10018 WELD METAL AND RELATED SPECIFICATIONS

Property	Weld deposit	10018-M*	11018-M*	10018-M1+
Yield stress (MPa) (estimated at 20°C)	625-655	607-689	676-758	565-648
Tensile strength (MPa) (estimated at 20°C)	740-770	689 min	758 min	-
Elongation (%)	27-30	20 min	20 min	20 min
R of A (%)	68	-	-	-
Charpy impact energy				
J at -18°C	103-111			81
J at -51°C	85 (min estimate)	27	48	48
Dynamic tear energy				
J at -29°C	>678	-	-	407 min

* MIL-E-0022200/1F (SH)

\+ MIL-E-0022200/10A (SH)

TABLE 8. MECHANICAL PROPERTIES, SECOND TEST SERIES

1. TENSILE TESTS (-18°C) WELD METAL

Test Piece	0.2% Proof Stress	Tensile Strength	Elong. on 4 d. (%)	Redn. of Area (%)
Transverse				
Top weld	645	755	23	68
Bottom	640	750	22	74
Longitudinal				
Top weld	645	750	26	67
Bottom	645	735	27	70

2. CHARPY V-NOTCH TESTS WELD METAL

J at - 18°C 78-115
J at - 51°C 45-75 (estimated spread)

3. DYNAMIC TEAR TESTS (-29°C)

Specimen No.	Energy Absorbed (J)	Extent of cracking (% of thickness)
Weld Metal		
1	570	20
2	636	90
3	610	60
4	637	40
Parent Plate		
1	679	0
2	813	5

TABLE 9. RESULTS OF SECOND SERIES EXPLOSION BULGE TESTING. ALL PLATES PASSED EASILY

Plate No.	Charge (Pentolite) (Kg)					Reduction in Thickness (%)					Bulge Depth (mm)				
	Blast No.					Blast No.					Blast No.				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Crack Starter 1	15.4	15.4	15.7			2.5*	9.3*	13.4*			42	77	119		
Crack Starter 2	15.1	15.3				2.6*	7.5*				41	82			
Explosion Bulge 1	15.6	15.4	15.5	9.8	16.5	2.9	8.0	13.8*	18.1*	29.9*	41	73	102	115	144
Explosion Bulge 2	16.4	15.4	16.2	15.2		2.9	6.4	10.6*	18.0*		37	68	97	118	
Explosion Bulge 3	15.4	15.3	15.0	15.2	16.5	2.4	6.7	12.4*	16.0*	24.0*	37	69	85	113	138
Explosion Bulge 4	15.4	16.5	16.5	16.5	15.5	2.2	6.0	10.7*	16.0*	25.7*	38	64	90	113	136

* Plate showed Cracking

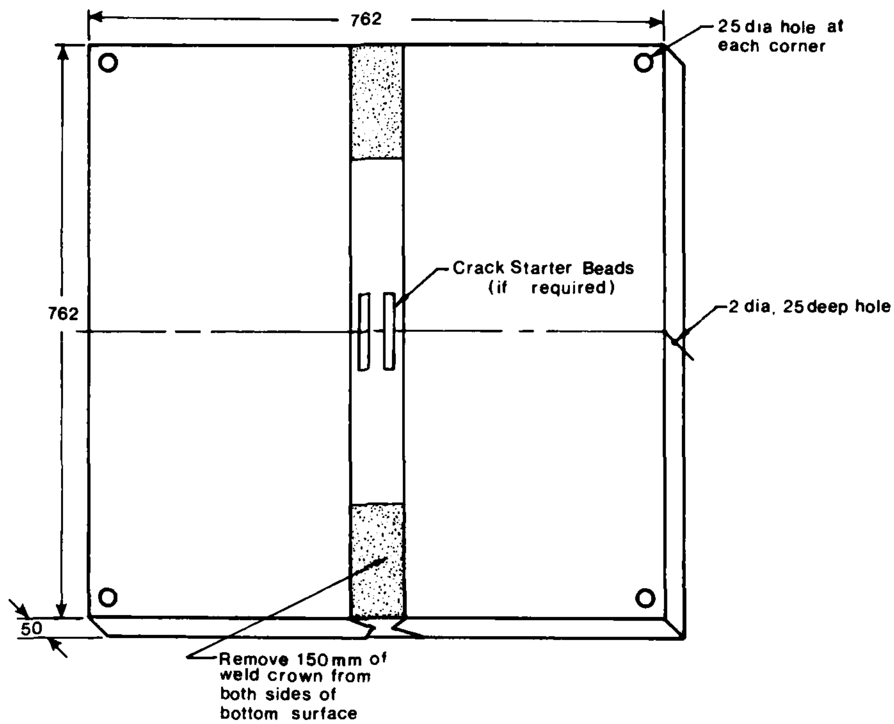


FIGURE 1 Design of explosion bulge test plate. Crack starter beads are only required for crack starter tests. Dimensions are in mm.

FIGURE 2 Die block in position over base plate.

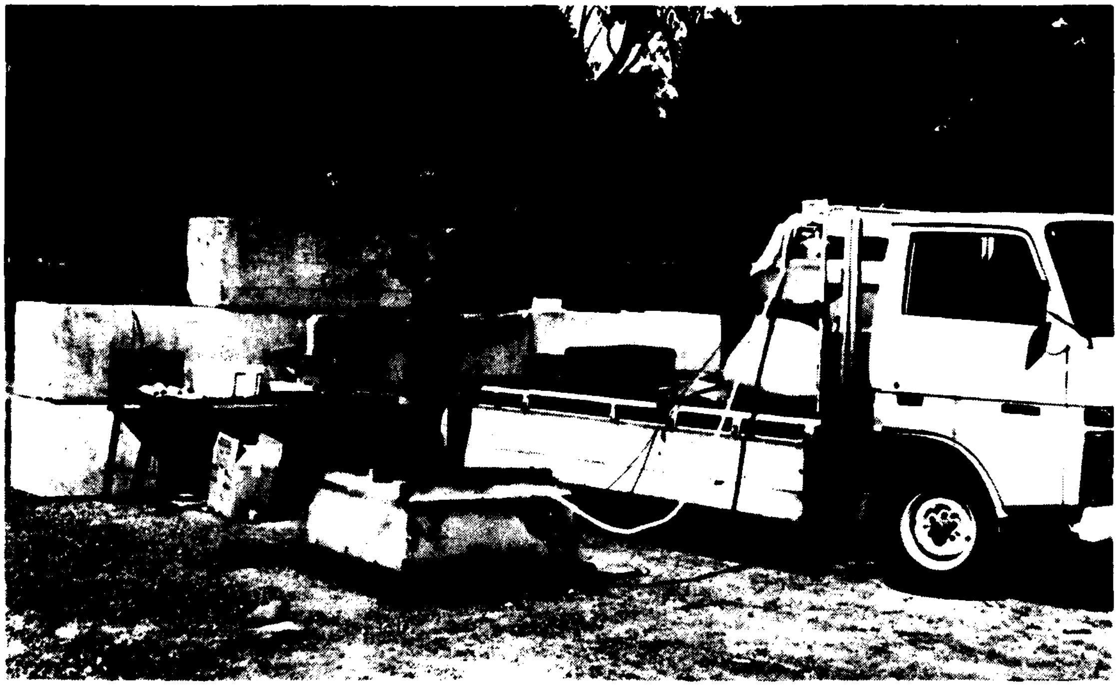


FIGURE 3 Arrangement for pumping liquid nitrogen into the plate cooling box. Truck and equipment is protected from the blast by a wall constructed of concrete "pentane" blocks.

FIGURE 4 Blasting set-up. Inserting detonator into explosive charge, which is located on a flimsy wooden table over the centre of the plate. The test plate is white with frost cover. Thermocouple is inserted into front edge of test plate, with compensating lead protected by the angle-iron.

FIGURE 5 Bottom surface of plate 2 (Series 1) showing the ring marking the line of contact between the plate and die block at the time of blasting. A plate fails the test if cracking extends outside this ring (as shown here).

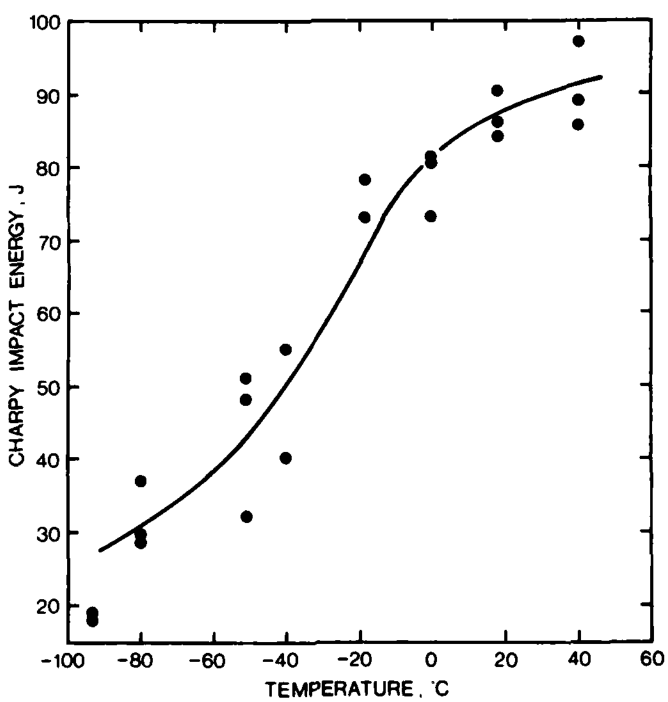


FIGURE 6 Charpy impact transition curve for weld metal used in the first series of tests.

FIGURE 7. Part-section across weld removed from first series test plate. Cracking was largely insensitive to microstructure. Magnification X2.

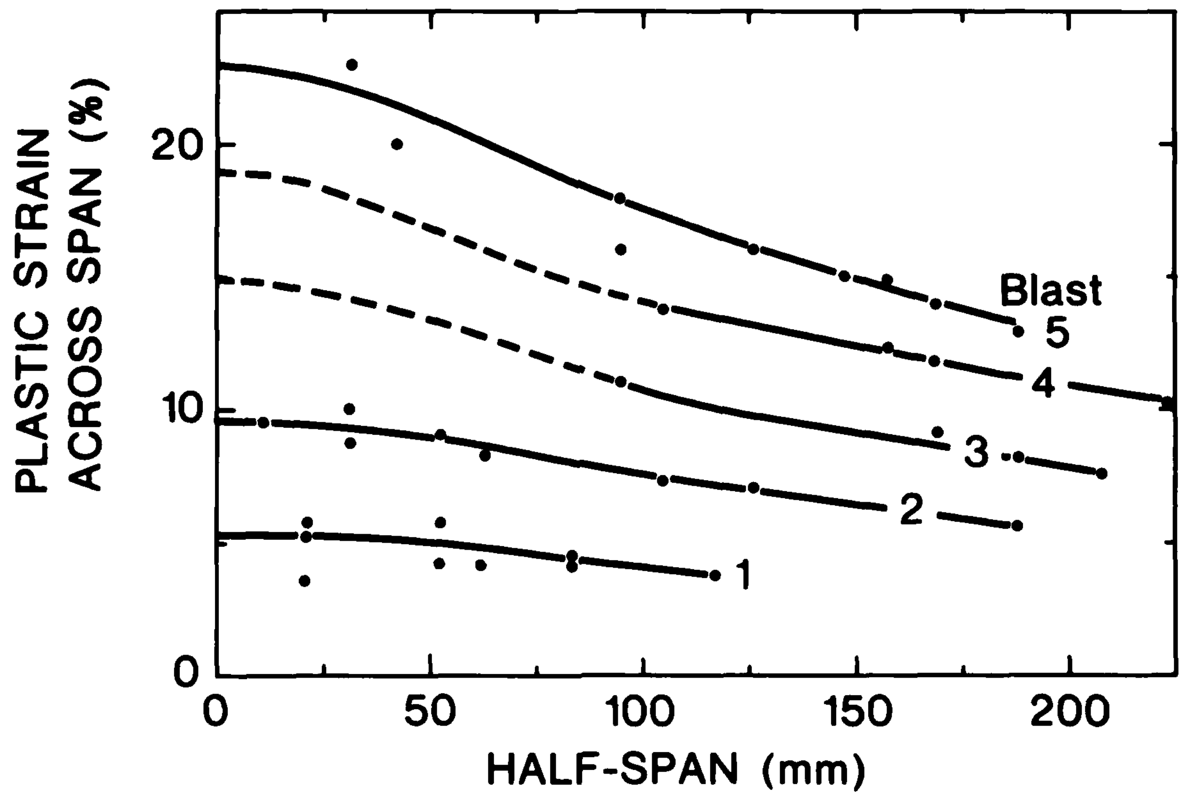


FIGURE 8 Development of surface strains across the bulge convex surface. Distance is measured from centre of the bulge.

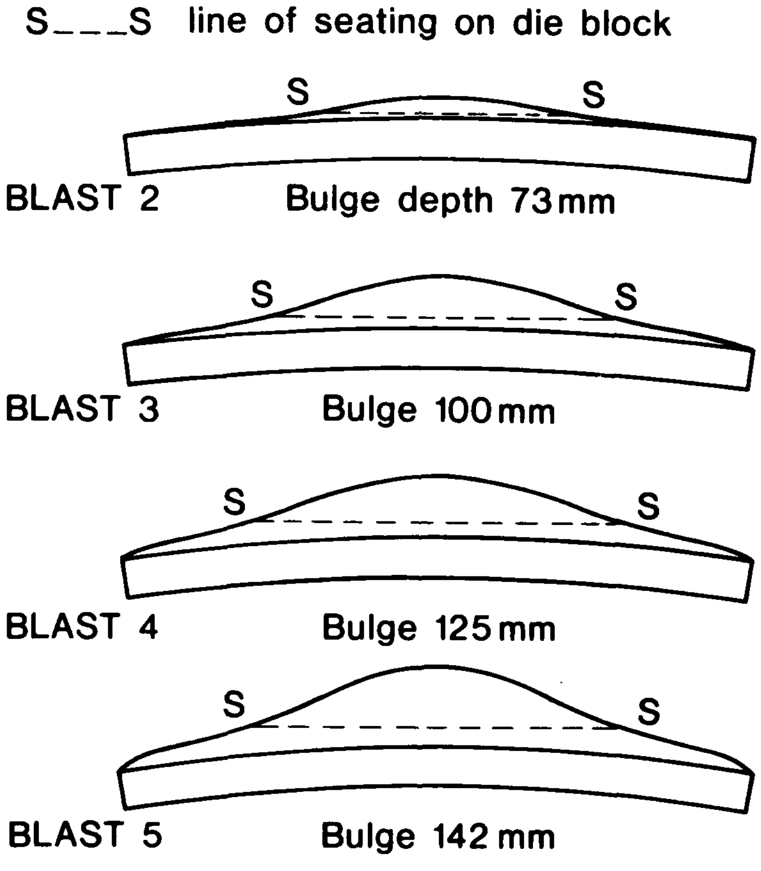


FIGURE 9 Tracings from photographs of unwelded test plate profiles after each explosion.

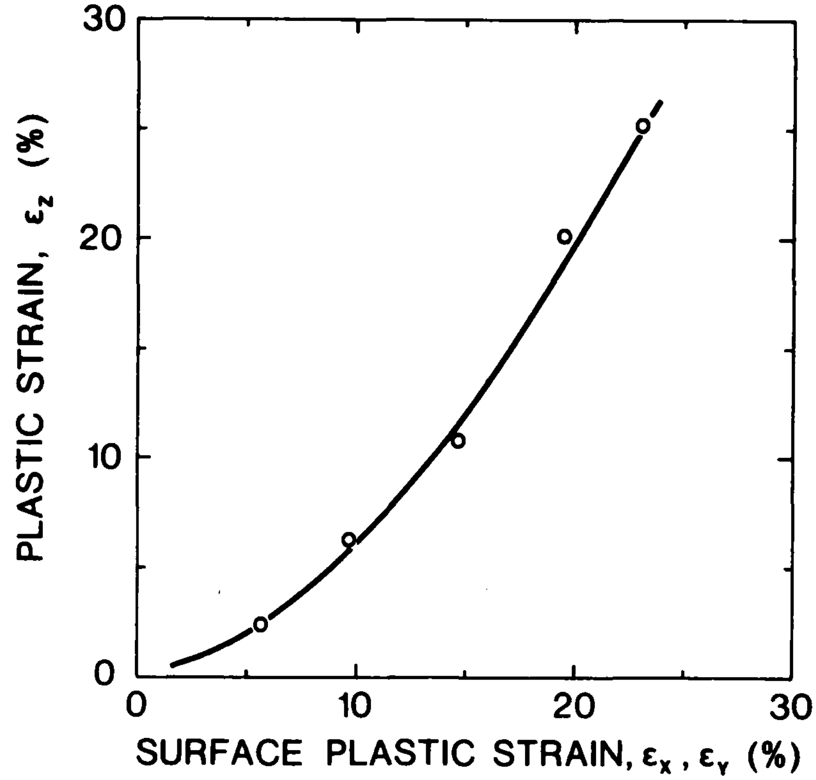


FIGURE 10 Relationship of plastic strains in the explosion bulge test.

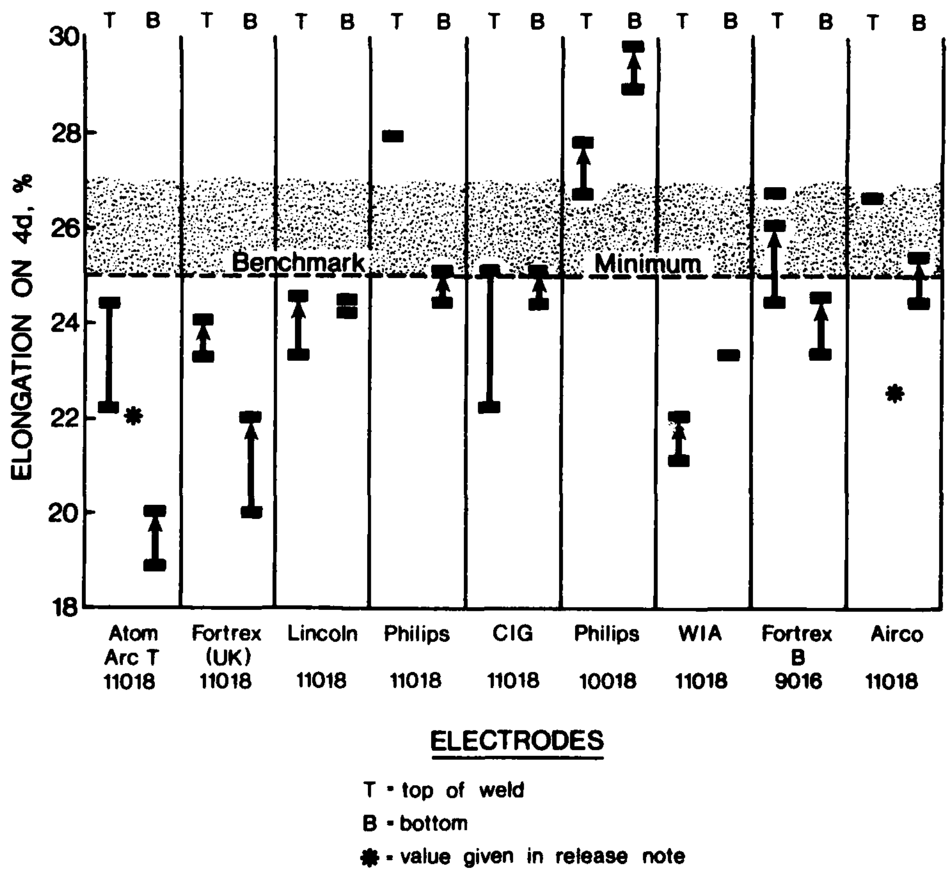


FIGURE 11 Comparative ductility of HY-80 consumables. Benchmark is determined from experiences with the first series of tests, the unwelded plate and information from Alm [6].

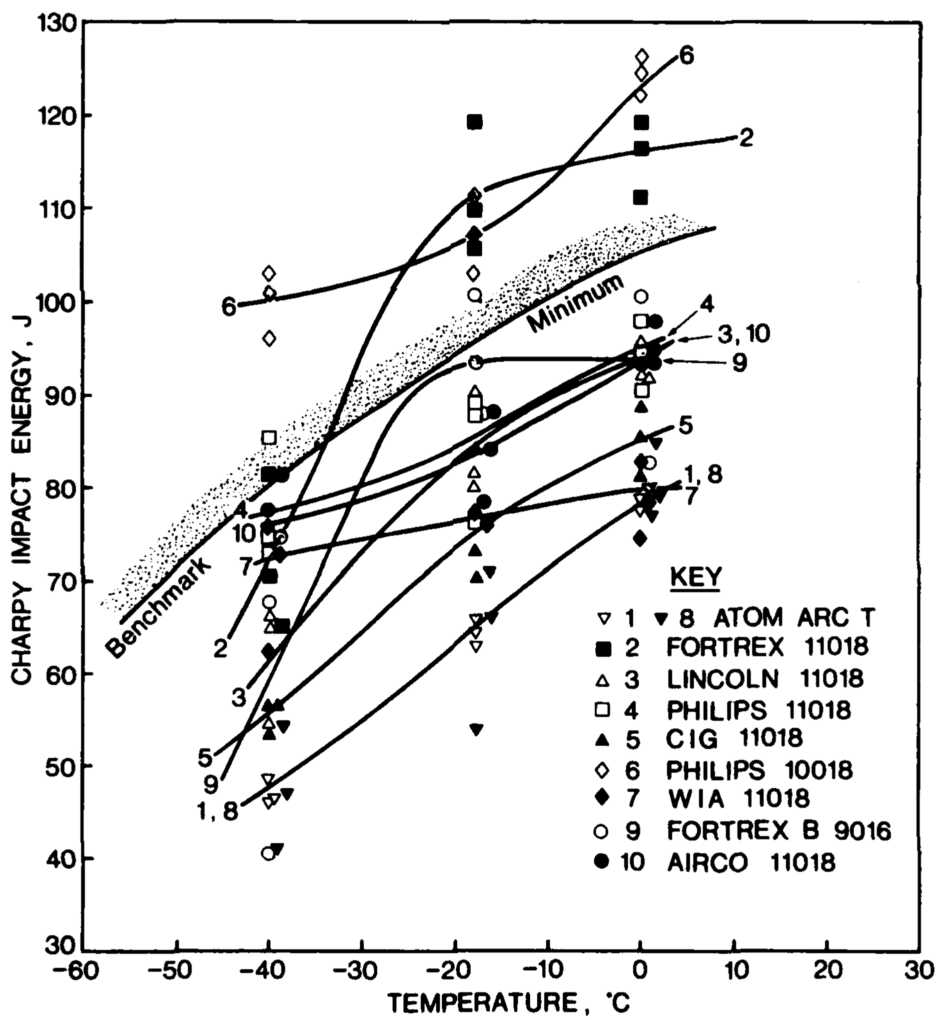


FIGURE 12 Charpy V-notch impact results for HY-80 consumables. Benchmark was determined as with Fig 11.

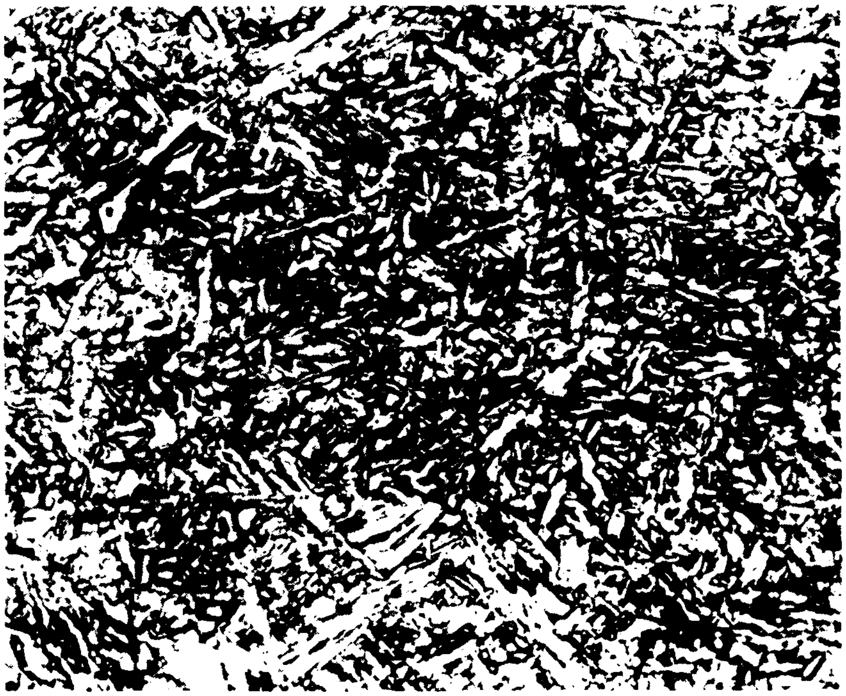
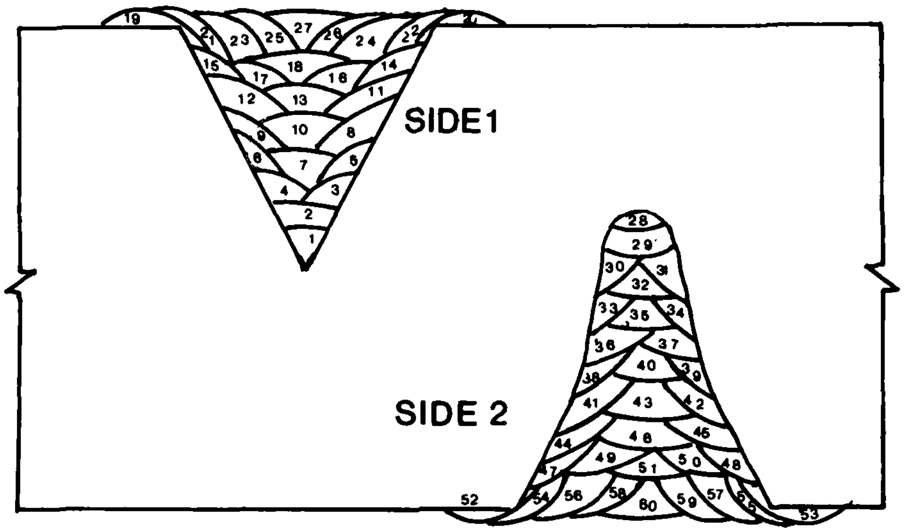


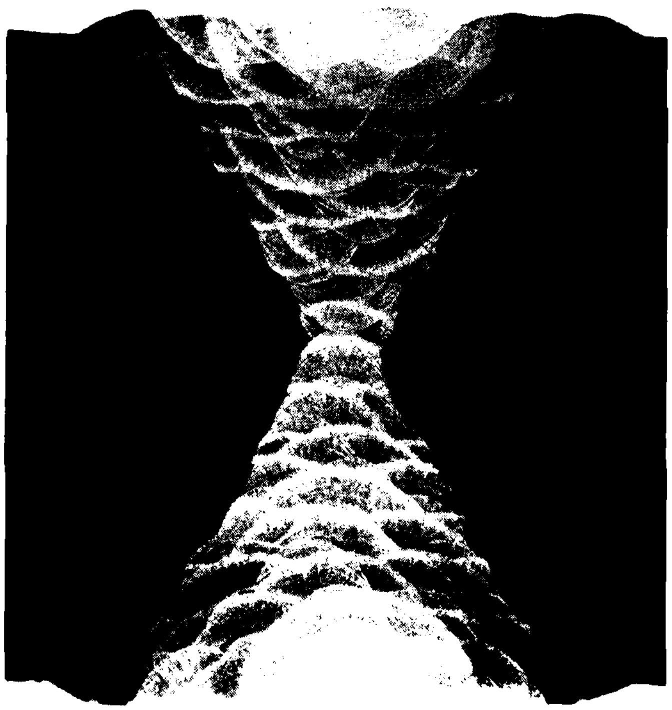
FIGURE 13 Microstructure of Philips 10018 weld deposit.
ECHANT: Acid ferric chloride X1000.



A

Backgouge side two 6 mm, grind and dye check before depositing weld metal

<u>Welding conditions</u> Current: 160-200 A*, AC or DC. (DC for capping passes)
Voltage: 23-26 V
Travel Speed: 160-300 $mm.min^{-1}$ (stringer bead)*
Preheat/Interpass Temp: 150°C
*: except for first pass



B

FIGURE 14 Optimum welding procedure.
A: weld sequence
B: photomacrograph x 1.7

Features include:

(a) low heat input "stringer bead" technique for each weld.
(b) welding sequence chose so that, as nearly as possible, each weld travels along the toe of a preceding one
(c) at each layer welds progress from the side of the joint towards the centre
(d) weld crown is kept low
(e) "Top-hat" technique is used.

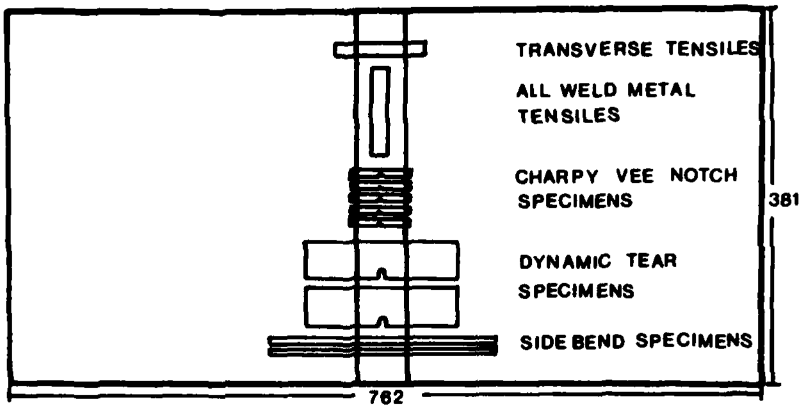


FIGURE 15 Location of mechanical test specimens in mechanical test weldment. With the exception of the side bend specimens, test pieces are removed from both sides of the plate. Dimensions are in mm.

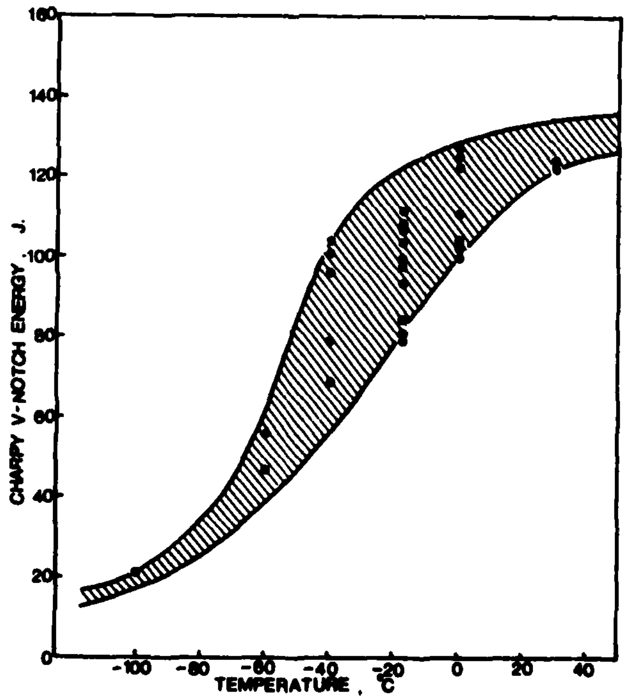


FIGURE 16 Charpy transition curve for weld metal used in the second series of tests.

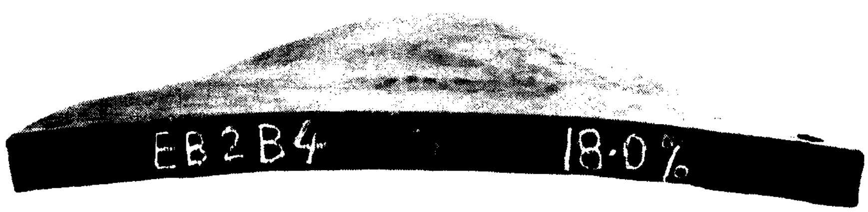
(a)

(b)

FIGURE 17 Explosion bulge plate number 1, at completion of testing.

(a) plan
(b) elevation

(a)

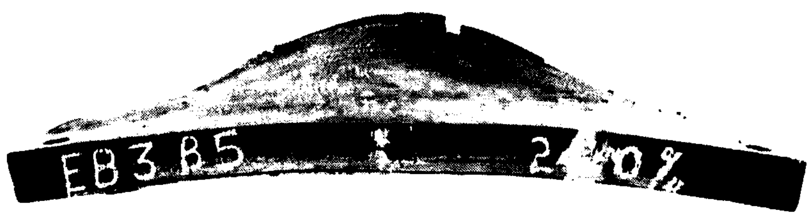


(b)

FIGURE 18 Explosion bulge plate number 2, at completion of testing.

(a) plan
(b) elevation

(a)



(b)

FIGURE 19 Explosion bulge plate number 3, at completion of testing. Section removed from the centre of the plate was for metallographic examination (see Fig. 21).

(a) plan
(b) elevation

(a)

(b)

FIGURE 20 Explosion bulge plate number 4, at completion of testing.

(a) plan
(b) elevation

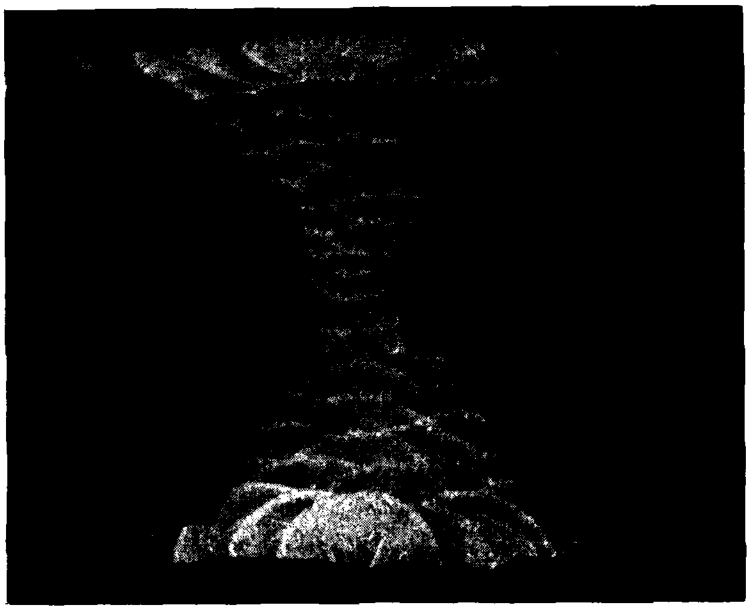


FIGURE 21. Section removed from plate number 3 showing the influence of the top-hat design. Cracks extending from both weld toes travelled into ductile parent metal and therefore developed a slant fracture mode. Magnification x 1.5.

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